Asynchronous Probing Scheme for the Optimal Energy-Efficient Neighbor Discovery in Opportunistic Networking

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Abstract—In opportunistic networking, it is hard to predict when a node gets and how long it keeps in contact with another. The persistent probing for prompt neighbor discovery consumes too much energy for battery-operated devices to afford. The most important issue is to carefully manage the power states at all stages of network operations. For the problem consisting of one sender and one receiver, we have presented a novel neighbor discovery scheme which is optimal in a sense that it does not miss a contact with the minimum energy consumed. In this paper, we extend the previous result to the optimal neighbor discovery scheme for the general case.

I. Introduction

In opportunistic networking, most devices are battery-operated so that their radio coverage is limited and data is exchanged only through contacts that occur infrequently [1]. Furthermore, they cannot afford persistent probing to discover neighbors in contact. A feasible solution could be to turn off the radio during non contact time and to turn it on only for neighbor discovery and data exchange. It is difficult to accurately predict when the nodes encounter each other and how long they remain in contact, while it is important to find such figures for efficient energy consumption.

To save energy, the power states for network operations should be prudently managed. In [2] and [3], the prompt neighbor discovery was suggested without the sleeping mode. In contrast, an optimal wake-up schedule with the sleep mode is designed in [4]. They proposed the schedule with two states of sleep and wakeup. However, it is not sufficient to be energy-efficient because it does not specify what to do in the wakeup state. We believe the wakeup state must be elaborated depending on the action the node takes to be energy efficient.

In [5], we define two states instead of the wakeup state; probing and listening. Then, we have simplified the problem consisting of one sender and one receiver and obtained its optimal solution in the total energy consumption. We have shown that the optimal neighbor discovery scheme guarantees the minimum energy consumption and neighbor discovery within the delay bound D. The delay bound D is defined as the upper bound in discovering the neighbor nodes, that is, the time difference between the instant of discovering the contact and the instant of initializing physical contact.

However, it is very restricted to assume that two meeting nodes are configured as one being a sender and the other being a receiver. Since nodes are potentially senders and receivers, they operate in one among three states (probing, listening, and sleeping) with identical neighbor discovery schedule. Hence, we extend this scheme in order that two nodes which have some data to send can discover each other within the delay bound D and exchange their data. The delay bound can be given as a constant [6], [7] or can be probabilistically derived [2], [8]. If D is obtained from the contact duration distribution, it is a probabilistic threshold. This implies that our scheme probabilistically guarantees that two adjacent nodes discover each other within D.

The remainder of this paper covers the brief introduction of our previous result in [5], its extension for the general case, and the performance evaluation through theoretical analysis and simulations.

II. Optimal Neighbor Discovery Scheme: One Sender and One Receiver

We assume that node S keeps probing and node R keeps listening. Node S sends probing messages for interval a_i and then sleeps for interval b_i. Similarly, node R listens to receive probing messages for interval c_j and then sleeps for interval d_j. Note that these intervals may be determined arbitrarily according to a scheduling policy. Let E_P, E_L, and E_S ($E_P > E_L \gg E_S$) denote respectively the energy consumed in probing, listening, and sleeping mode. Then, the total energy E_{total} can be expressed as

$$E_{total} = \sum_{i=1}^{M} (E_P \cdot a_i + E_S \cdot b_i) + \sum_{j=1}^{N} (E_L \cdot c_j + E_S \cdot d_j).$$

Without loss of generality, we can assume that node S and node R operate for interval T such that $\sum_{i=1}^{M} (a_i + b_i) = \sum_{j=1}^{N} (c_j + b_j) = T$, where M and N are the number of probing intervals and listening intervals in T respectively. Given D, the problem is to find how to schedule probing and listening for neighbor discovery with the minimum energy consumed.
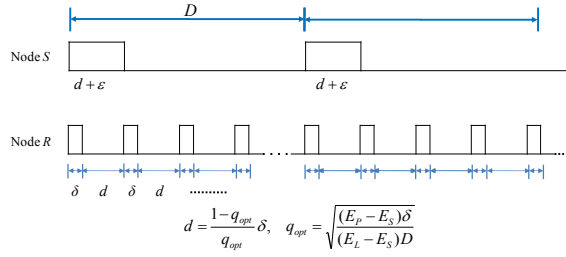
Fig. 1. Optimal probing & listening schedule with optimal duty cycle

Fig. 2. Case 2: Location of a probing interval in asynchronous systems

Through the analytical exploration of the total energy consumption, we have proposed the optimal probing & listening schedule and derived the optimal duty cycle. The total energy consumption is minimized when we schedule every sleeping interval d_j for node R to be constant d and each probing interval a_i to be $d + \epsilon$, where ϵ is a small amount of interval. With duty cycle q for node R, every listening interval c_i is set to δ, then $d = \frac{1-q}{q}\delta$. Note that δ is the smallest interval required by node R to recognize a probing message. With respect to q, the minimum energy consumption can be obtained through derivative test. With duty cycle q for node R, the optimal duty cycle can be derived as

$$q_{opt} = \sqrt{\frac{(E_P - E_S)\delta}{(E_L - E_S)D}}.$$

The Fig. 1 shows the optimal neighbor discovery scheme with optimal duty cycle in case of one sender and one receiver.

III. EXTENSION OF THE OPTIMAL NEIGHBOR DISCOVERY SCHEME FOR THE GENERAL CASE

In this section, we extend the optimal neighbor discovery scheme for the general case. A basic assumption that two meeting nodes are configured as one being a sender and the other being a receiver is not realistic. Generally, every node has to participate in probing, listening, and sleeping since it always has some data to send in opportunistic networking. However, because nodes cannot probe, listen, and sleep simultaneously, they must switch among three states. Therefore, a probing message may be lost. For example, if two nodes' schedules are identical or the listening time is too short to completely understand a probing message, a loss of a probing message happens. We explain that the loss probability of a probing message is determined by the size of the probing interval and the schedule among three operations. Then, we suggest a scheme for reducing the loss probability into minimum.

A. Optimal neighbor discovery scheme for the general case

The asynchronous mechanisms are widely used due to their simplicity. In addition, compared to the synchronous system, they have an absolute advantage in that they are required to maintain synchronous clocks or align slot boundaries. In opportunistic networks, nodes are not allowed to perform synchronization because they may be initiated at different times and be intermittently connected for a relatively short duration.
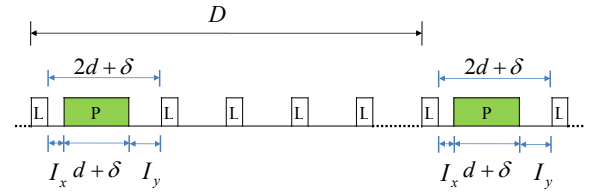
These features make asynchronous mechanisms suitable for opportunistic networking.

From section II, we can infer that the sleeping and listening intervals are set to d and δ, respectively, and the probing interval is given $d + \epsilon$. For the general case, every node must be designed to be able to efficiently perform both roles of node S and node R. If they do so, the success probability of neighbor discovery decreases.

A loss of a probing message may occur if a probing interval is equal to or smaller than a sleeping interval. In addition, if the recognition time of a probing message μ is shorter than δ, node R cannot completely understand the probing message. The loss probability of a probing message varies with the size of a probing interval ($= d+\epsilon$). For the general case, we analyze the loss probability with three sizes of ϵ.

a) Case 1: $\epsilon = 0$

It is easy to locate the probing interval between the first and second listening intervals of every D. If two nodes randomly meet within D, a probing message cannot be recognized with the probability of $2\delta/D$ within every listening and sleeping interval. Hence, the probability of a probing message, P_{LP} in case 1 is calculated as

$$P_{LP} = \underbrace{\frac{2\delta}{D} + \cdots + \frac{2\delta}{D}}_{n} = \frac{2n\delta}{D}.$$

b) Case 2: $\epsilon = \delta$

In case 2, since the probing interval is longer than the sleeping interval, the probing interval must be located between the first and third listening intervals, as shown in Fig. 2. The loss probability of a probing message depends on the positioning of the probing interval. The interval between the first listening and the first probing interval is denoted by I_x, and the interval between the probing and the next listening interval is denoted by I_y. While the loss of a probing message may be caused by the removal of one listening interval, the size of the probing interval that is increased by δ reduces P_{LP}. As a result, P_{LP} in case 2 is expressed as

$$P_{LP} = \begin{cases} \frac{2(I_x+\delta)}{D} + \underbrace{\frac{\delta}{D} + \cdots + \frac{\delta}{D}}_{n-2} = \frac{2I_x+n\delta}{D} & , I_x < I_y \\ \frac{2(I_y+\delta)}{D} + \underbrace{\frac{\delta}{D} + \cdots + \frac{\delta}{D}}_{n-2} = \frac{2I_y+n\delta}{D} & , I_x \geq I_y \end{cases}.$$

In order to minimize P_{LP}, I_x or I_y has to be set to 0. Then, the minimum of P_{LP} is $n\delta/D$, where $n \geq 2$.
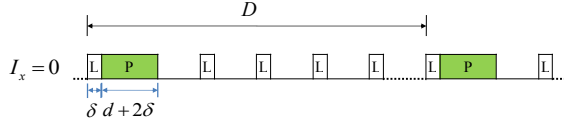
c) Case 3: $\epsilon = 2\delta$

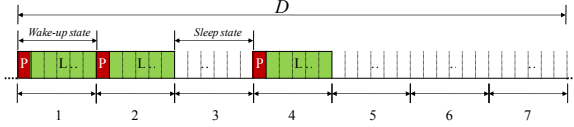Fig. 3. Probing interval and location for the general case

Fig. 4. WSF-(7,3,1) schedule structure

In case 3, P_{LP} is calculated in a similar manner as case 2. Hence, P_{LP} can be expressed as

$$P_{LP} = \begin{cases} \dfrac{2(I_x + \delta)}{D} & , I_x < I_y \\ \dfrac{2(I_y + \delta)}{D} & , I_x \geq I_y \end{cases} .$$

The minimized P_{LP} can be obtained as $2\delta/D$ by setting I_x or I_y to 0. From these three cases, we can deduce that the method in case 3 minimizes the loss probability of a probing message ($= 2\delta/D$) while it maintains the optimal probing and listening schedule of a given duty cycle in section II as shown in Fig. 3.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed neighbor discovery scheme and two wake-up schedules of [4] through theoretical analysis and simulations. We compare the proposed scheme with two wake-up schedule functions in [4]: WSF-(7,3,1) and WSF-(73,9,1). In [4], the wake-up schedules for different delay bounds can be obtained. It is sufficient to compare the proposed scheme with a few wake-up schedules for relatively short D because contact durations are instant in most cases. As illustrated in Fig. 4, (7,3,1) provides the method that guarantees one chance for exchanging data by waking up for 3 periods out of 7 periods.

For the comparison of energy consumption, we use the average energy consumption during a given delay bound D for the neighbor discovery. The average energy consumptions during D of the proposed scheme, (7,3,1) and (73,9,1) are easily expressed as

$$\begin{aligned} E_{Proposed} &= E_P(d+2\delta) - E_L\delta - E_S(d+\delta) \\ &\quad + D(E_L q_{opt} + E_S(1-q_{opt})) \\ E_{WSF-(7,3,1)} &= 3E_P\delta + 3E_L(\tfrac{D}{7}-\delta) + (7-3)\tfrac{D}{7}E_S \\ E_{WSF-(73,9,1)} &= 9E_P\delta + 9E_L(\tfrac{D}{73}-\delta) + (73-9)\tfrac{D}{73}E_S . \end{aligned}$$

We observe a significant energy saving using the proposed scheme as shown in Fig. 5. Although (73,9,1) consumes a similar amount of energy with the proposed scheme at $D = 350$, it cannot be applicable in real systems because of a low success probability of neighbor discovery as shown in Fig. 6. To evaluate the success probability of neighbor discovery, we conducted simulations. To clarify the performance evaluation,
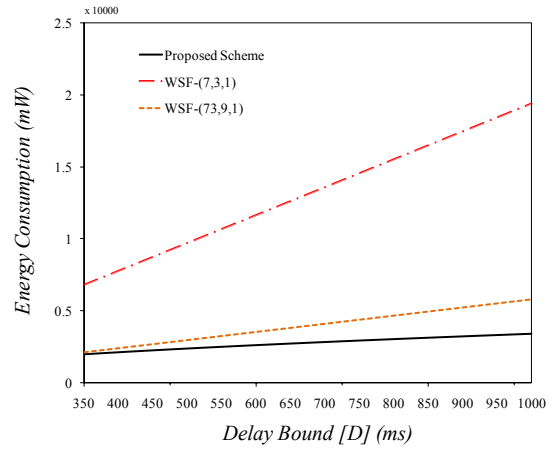

Fig. 5. Energy consumption

we simplify the simulation model as follows. The network consists of 30 nodes randomly placed over a $500m \times 500m$ grid. The power consumptions of probing, listening and sleeping are $60mW$, $45mW$ and $0.09mW$, respectively. The transmission range is set to $50m$. The node velocity is uniformly distributed in (3m/s, 5m/s). Nodes move according to the random walk mobility model. The schedules are divided into equal intervals minimally required for the sending or receiving of a probing message, which are set to 1 ms ($= \delta$). To verify the credibility of the simulation, we derive the success probabilities of neighbor discovery of the proposed scheme, (7,3,1) and (73,9,1) as

$$\begin{aligned} P_{SD\_Proposed} &= 1 - \delta/D \\ P_{SD\_WSF-(7,3,1)} &= 1 - 7\delta/D \\ P_{SD\_WSF-(73,9,1)} &= 1 - 73\delta/D . \end{aligned}$$

As shown in Fig. 6, the simulation results almost overlap with the obtained probabilities. The success probability of the proposed scheme is nearly 1 and always higher than (7,3,1) and (73,9,1). Although all success probabilities approach 1 as D increases, the proposed scheme saves energy more significantly than two schemes. Consequently, the proposed scheme not only achieves more energy-efficiency but also higher success probability than (7,3,1) and (73,9,1).

V. CONCLUSION

We proposed an optimal neighbor discovery scheme that guarantees the completion of neighbor discovery within D with minimum energy consumed. Further, we extended the optimal neighbor discovery scheme for the general case. Theoretical analysis and simulations demonstrate that the proposed scheme achieves a significant energy-efficiency and provides high success probability neighbor discovery.
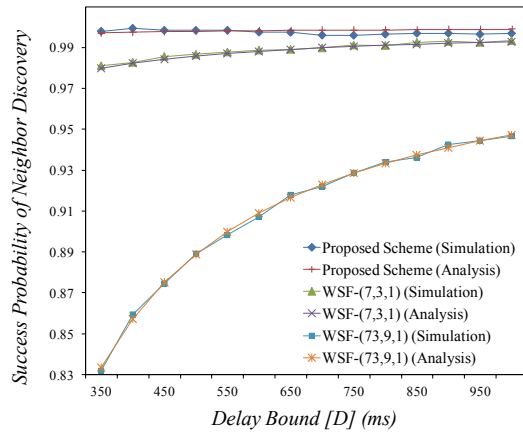
Fig. 6.   Success probability of neighbor discovery

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